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The Polarization Asymmetry and Triple Gauge Boson Couplings in γe Collisions at the NLC

Thomas G. Rizzo[1]

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309 USA

ABSTRACT

We examine the capability of the NLC in the γe collider mode to probe the CP-conserving γWW and γZZ anomalous couplings through the use of the polarization asymmetry. When combined with other measurements, very strong constraints on both varieties of anomalous couplings can be obtained.

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1 Introduction

The Standard Model(SM) has so far done an excellent job at describing almost all existing data. One of the most crucial remaining set of tests of the gauge structure of the SM will occur at future colliders when precision measurements of the various triple gauge boson vertices(TGVs) become available[1]. If new physics arises at or near the TeV scale, then on rather general grounds one expects that the deviation of the TGVs from their canonical SM values, *i.e.*, the anomalous couplings, to be *at most* $\mathcal{O}(10^{-3}-10^{-2})$ with the smaller end of this range of values being the most likely. To get to this level of precision, and beyond, for all of the TGVs a number of different reactions need to be studied using a variety of observables. Here we concentrate on the CP-conserving γWW and γZZ anomalous couplings that can be probed in the reactions $\gamma e \rightarrow W\nu, Ze$ at the NLC using polarized electrons and polarized backscattered laser photons[2]. In the γWW case, the anomalous couplings modify the magnitude and structure of the already existing SM tree level vertex. No corresponding tree level γZZ vertex exists in the SM, although it does appear at the one-loop level. One immediate advantage of the $\gamma e \rightarrow W\nu$ process over, *e.g.*, $e^+e^- \rightarrow W^+W^-$ is that the γWW vertex can be trivially isolated from the corresponding ones for the ZWW vertex, thus allowing us to probe this particular vertex in a model-independent fashion. To set the notation for what follows, the γWW and γZZ anomalous couplings are denoted by $\Delta\kappa$, λ and $h^0_{3,4}$[1], respectively. We will assume that the γWW and γZZ anomalous couplings are unrelated; the details of our analysis can be found in Ref.[2].

2 Analysis

The use of both polarized electron and photon beams allows one to construct a polarization asymmetry, A_{pol}. In general the $\gamma e \rightarrow W\nu, Ze$ (differential or total) cross sections can be written schematically as $\sigma = (1 + A_0 P)\sigma_{un} + \xi(P + A_0)\sigma_{pol}$, where P is the electron's polarization(> 0 for left-handed beams), $-1 \leq \xi \leq 1$ is the Stoke's parameter for the circularly polarized photon, and A_0 describes the electron's coupling to the relevant gauge boson[$A_0 = 2va/(v^2 + a^2) = 1$ for W's and $\simeq 0.145$ for Z's, with v, a being the vector and axial-vector coupling of the electron]. $\sigma_{pol}(\sigma_{un})$ represents the polarization (in)dependent contribution to the cross section, both of which are functions of only a single dimensionless variable at the tree level after angular integration, *i.e.*, $x = y^2 = s_{\gamma e}/M^2_{W,Z}$, where $\sqrt{s_{\gamma e}}$ is the $\gamma - e$ center of mass energy. Taking the ratio of the ξ-dependent to ξ independent terms in σ gives us the asymmetry A_{pol}.

One reason to believe *a priori* that A_{pol}, or σ_{pol} itself, might be sensitive to modifications in the TGVs due to the presence of the anomalous couplings is the Drell-Hearn Gerasimov(DHG) Sum Rule[3]. In its $\gamma e \rightarrow W\nu, Ze$ manifestation, the DHG sum rule implies that

$$\int_1^\infty \frac{\sigma_{pol}(x)}{x} dx = 0\,, \tag{1}$$

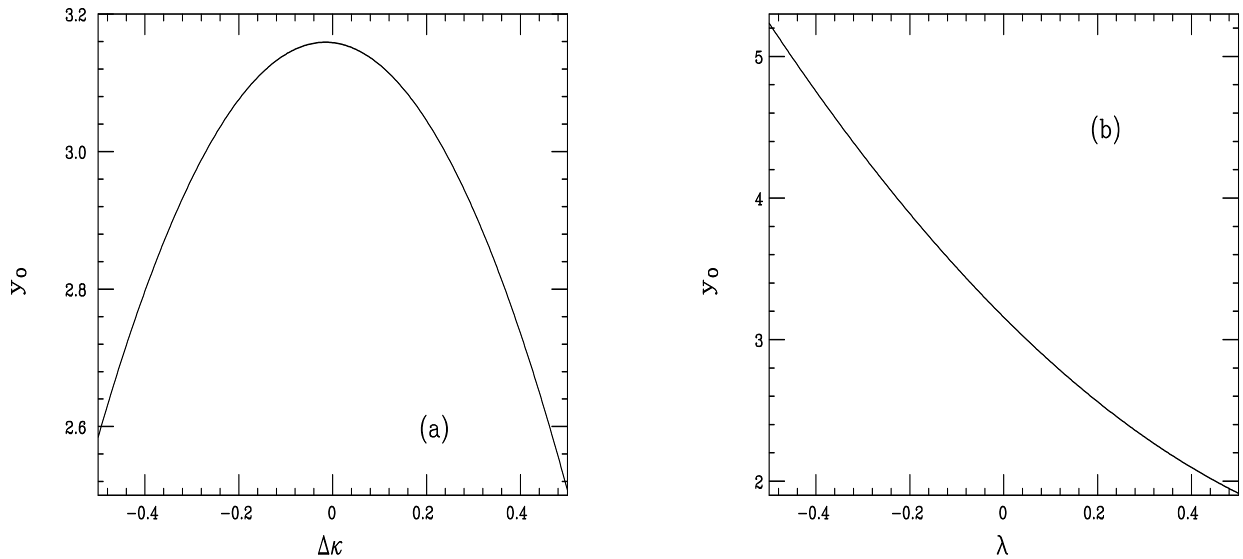

Figure 1: Separate $\Delta\kappa$ and λ dependence of the value of y_0, the zero position for the process $\gamma e \to W\nu$.

for the tree level SM cross section when the couplings of all the particles involved in the process are 'canonical', *i.e.*, gauge invariant. That this integral is zero results from (i) the fact that σ_{pol} is well behaved at large x and (ii) a delicate cancellation occurs between the two regions where the integrand takes on opposite signs. This observation is directly correlated with the existence of a single value of x(or y) where σ_{pol}(and, hence, A_{pol}) vanishes. For the $W(Z)$ case this asymmetry 'zero' occurs at $\sqrt{s_{\gamma e}} \simeq 254(150)$ GeV, both of which are easily accessible at the NLC. As we will see, the inclusion of anomalous couplings not only moves the position of the zero but also forces the integral to become non-vanishing and, in most cases, *infinite*. Unfortunately, since we cannot go to infinite energies we cannot test the DHG Sum Rule directly. In the W case, the zero position, y_0, is found to be far more sensitive to modifications in the TGVs than in the Z case. The zero position as a function of $\Delta\kappa$ and λ for the $\gamma e \to W\nu$ process is shown in Fig.1 whereas the corresponding Z case is shown in Fig.2. In either situation, the position of the zero *alone* does not offer great sensitivity to the existence of anomalous couplings.(See Ref. 2.)

Our analysis begins by examining the energy, *i.e.*, y dependence of A_{pol} for the two processes of interest; we consider the W case first. For a 500(1000) GeV collider, we see that only the range $1 \leq y \leq 5.4(10.4)$ is kinematically accessible since the laser photon energy maximum is $\simeq 0.84E_e$. Since we are interested in bounds on the anomalous couplings, we will assume that the SM is valid and generate a set of binned A_{pol} data samples via Monte Carlo taking only the statistical errors into account. We further assume that the electrons are 90% left-handed polarized as right-handed electrons do not interact through the W charged current couplings. Our bin width will be assumed to be Δy =0.1 or 0.2. We

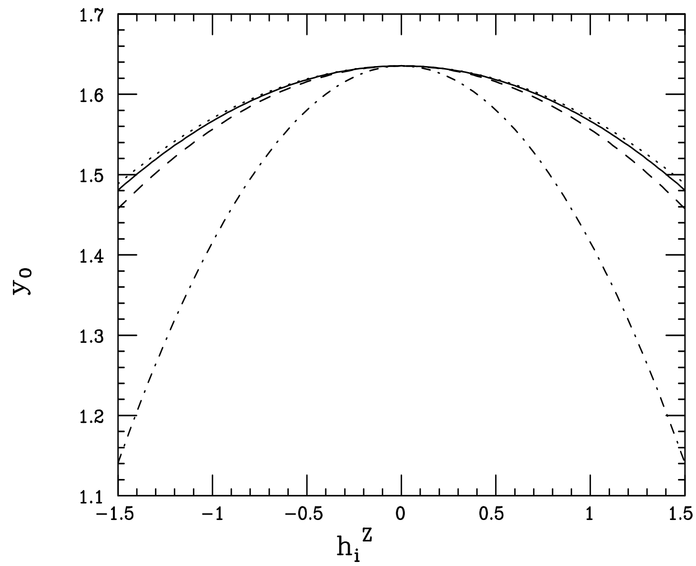

Figure 2: Position of the SM polarization asymmetry zero in $\gamma e \to Ze$ as a function of $h^0_{3,4}$ for $P = 90\%$ with a 10° angular cut. The dotted(dashed, dash-dotted, solid) curve corresponds to the case $h^0_4 = 0(h^0_3 = 0,\ h^0_3 = h^0_4,\ h^0_3 = -h^0_4)$.

then fit the resulting distribution to the $\Delta\kappa$- and λ-dependent functional form of $A_{pol}(y)$ and subsequently extract the 95% CL allowed ranges for the anomalous couplings. The results of this procedure are shown in Fig. 3, where we see that reasonable constraints are obtained although only a single observable has been used in the fit.

Clearly, to obtain stronger limits we need to make a combined fit with other observables, such as the energy dependence of the total cross section, the W angular distribution, or the W polarization. As an example we show in Fig. 4 that the size of the 95% CL allowed region shrinks drastically in the 1 TeV case when the cross section data is included in a simultaneous fit together with the polarization asymmetry. As is well known, the cross section is highly sensitive to $\Delta\kappa$ and thus the allowed region is highly compressed in that direction. We find that $\Delta\kappa$ is bounded to the range $-1.45 \cdot 10^{-3} \leq \Delta\kappa \leq 0.36 \cdot 10^{-3}$ while the allowed λ range is still rather large. The addition of the angular distribution and W polarization data to the fit is expected to reduce the size of this allowed region even further.

With these thoughts in mind, in the Z case we will follow a similar approach but we will simultaneously fit both the energy dependence of A_{pol} as well as that of the total cross section. (Later, we will also include the Z boson's angular distribution into the fit.) In this Z analysis we make a 10° angular cut on the outgoing electron and keep a finite form factor scale, $\Lambda = 1.5$ TeV, so that we may more readily compare with other existing analyses. (The

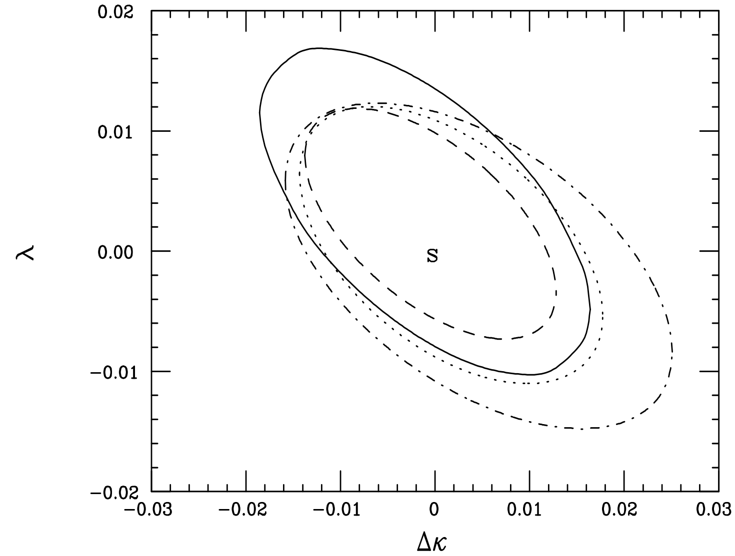

Figure 3: 95 % CL bounds on the W anomalous couplings from the polarization asymmetry. The solid(dashed, dash-dotted) curves are for a 500 GeV NLC assuming complete y coverage using 22(22, 44) bins and an integrated luminosity per bin of 2.5(5, 1.25)fb^{-1}, respectively. The corresponding bins widths are Δy =0.2(0.2, 0.1). The dotted curve corresponds to a 1 TeV NLC using 47 $\Delta y = 0.2$ bins with 2.5 fb^{-1}/bin. 's' labels the SM prediction.

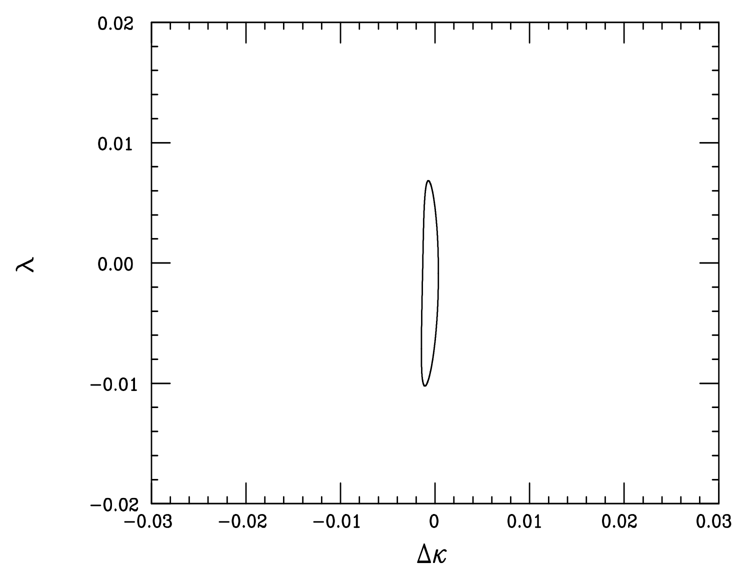

Figure 4: Same as the previous figure for a 1 TeV NLC but now combined with the cross section data in a simultaneous fit. Only statistical errors are included.

angular cut also gives us a finite cross section in the massless electron limit; this cut is not required in the case of the W production process.) We again assume that $P=90\%$ so that this analysis can take place simultaneously with that for the W. The accessible y ranges are now $1 \leq y \leq 4.6(9.4)$ for a 500(1000) GeV collider. Fig.5 shows our results for the 500 GeV NLC while Fig.6 shows the corresponding 1 TeV case. For a given energy and fixed total integrated luminosity we learn from these figures that it is best to take as much data as possible at the highest possible values of y. Generally, one finds that increased sensitivity to the existence of anomalous couplings occurs at the highest possible collision energies.

Even these anomalous coupling bounds can be significantly improved by including the Z boson angular information in the fit. To be concrete we examine the case of a 1 TeV NLC with $16.8 fb^{-1}$/bin of integrated luminosity taken in the last 10 Δy bins(corresponding to the dash-dotted curve in Fig.6). Deconvoluting the angular integration and performing instead the integration over the 10 Δy bins we obtain the energy-averaged angular distribution. Placing this distribution into 10 (almost) equal sized $cos\theta$ bins while still employing our 10° cut, we can use this additional data in performing our overall simultaneous χ^2 fit. The result of doing this is shown in Fig.7 together with the anticipated result from the LHC using the $Z\gamma$ production mode. Note that the additional angular distribution data has reduced the size of the 95% CL allowed region by almost a factor of two. Clearly both machines are complementary in their abilities to probe small values of the γZZ anomalous couplings. If the NLC and LHC results were to be combined, an exceptionally small allowed region would remain. The NLC results themselves may be further improved by considering measurements of the polarization of the final state Z as well as by an examination of, *e.g.*, the complementary $e^+e^- \rightarrow Z\gamma$ process; such studies are currently underway[4].

3 Discussion and Conclusions

The collision of polarized electron and photon beams at the NLC offers an exciting opportunity to probe for anomalous gauge couplings of both the W and the Z through the use of the polarization asymmetry. In the case of $\gamma e \rightarrow W\nu$ we can cleanly isolate the γWW vertex in a model independent fashion. When combined with other observables, extraordinary sensitivities to such couplings for W's are achievable at the NLC in the γe mode. These are found to be quite complementary to those obtainable in e^+e^- collisions. In the case of the γZZ anomalous couplings, we obtained constraints comparable to those which can be obtained at the LHC.

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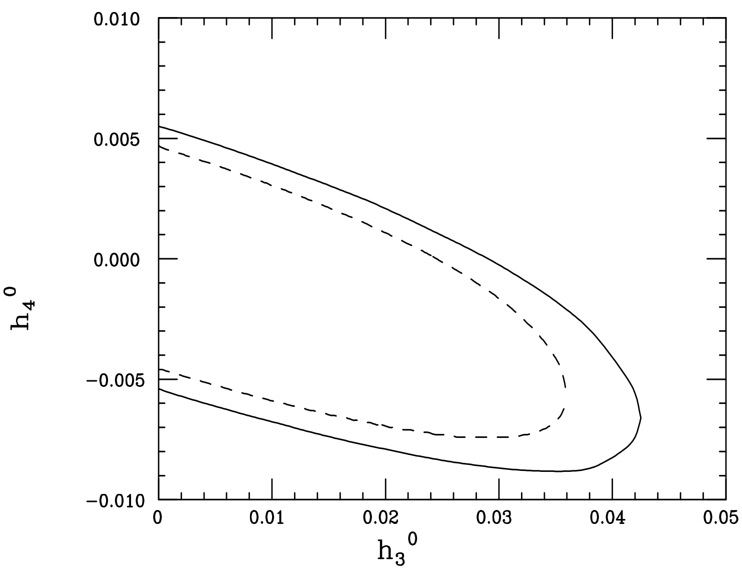

Figure 5: 95%CL allowed region for the anomalous coupling parameters h_3^0 and h_4^0 from a combined fit to the energy dependencies of the total cross section and polarization asymmetry at a 500 GeV NLC assuming $P = 90\%$ and an integrated luminosity of $3(6) fb^{-1}$/bin corresponding to the solid (dashed) curve. 18 bins of width Δy=0.2 were chosen to cover the y range $1 \leq y \leq 4.6$. The corresponding bounds for negative values of h_3^Z are obtainable by remembering the invariance of the polarization dependent cross section under the reflection $h_{3,4}^0 \to -h_{3,4}^0$.

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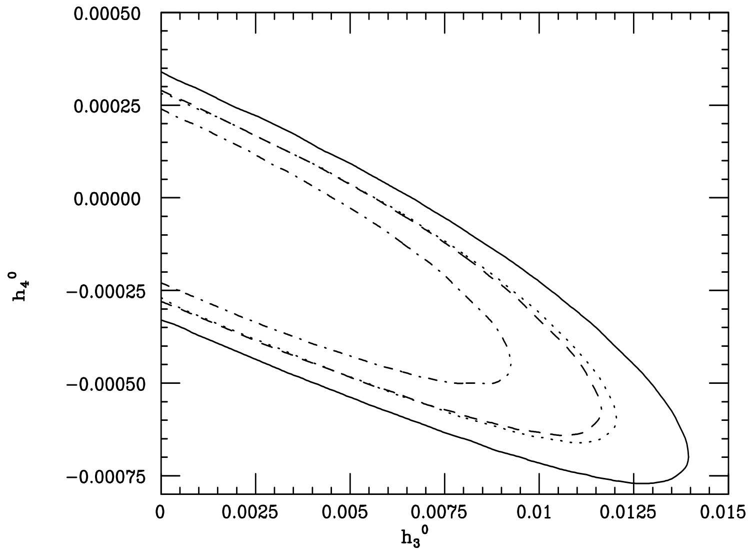

Figure 6: Same as Fig. 5 but for a 1 TeV NLC. The solid(dashed) curve corresponds to a luminosity of $4(8)fb^{-1}$/bin for 42 bins of width Δy=0.2 which covered the range $1 \leq y \leq 9.4$. The dotted curve corresponds to a luminosity of $8fb^{-1}$/bin but only for the last 21 bins. The dash-dotted curve corresponds to the case of $16.8fb^{-1}$/bin in only the last 10 bins.

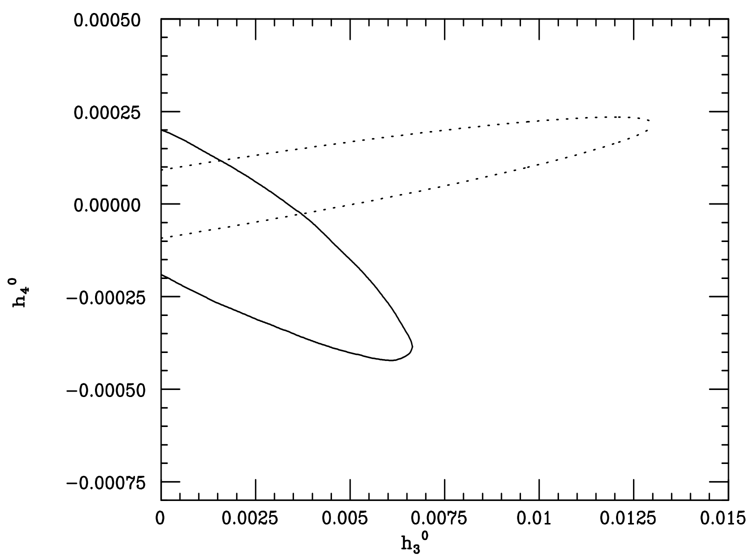

Figure 7: The solid curve is the same as dash-dotted curve in Fig. 6, but now including in the fit the Z boson angular distribution obtained from the highest 10 bins in energy. The corresponding result for the 14 TeV LHC with $100fb^{-1}$ of integrated luminosity from the process $pp \rightarrow Z\gamma + X$ is shown as the dotted curve.